Empirical Scaling Relations for Contained Single-Fired Chemical Explosions and Delay-Fired Mining Explosions at Regional Distances

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Sponsored by U.S. Department of Energy
Office of Nonproliferation and National Security
Office of Research and Development

Contract No. W-7405-ENG-48

ABSTRACT

Mining blasts are typically composed of numerous individual explosions that are detonated in a complex spatial and temporal pattern. For purposes of monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT), the signals from delay-fired mining explosions must be distinguished from those of a possible nuclear explosion. The similarity of seismic waveforms from contained chemical and nuclear explosions suggests that contained, single-fired chemical explosions can be used to calibrate the International Monitoring System. In order to address these issues, a series of experiments were designed and implemented in which single-fired explosions ranging in size from 5500 to 50000 lb. were detonated. The spatial separation of the individual explosions ranged from 30 m to over 4 km. Seismograms from the single-fired explosions were recorded within the mine (near-source) as well as at the IMS regional array PDAR (~360 km). Peak amplitudes for Pg, Pn and Lg phases at PDAR increased linearly with yield for the fully detonated single-fired explosions. In contrast, peak amplitude measurements from production coal and cast shots in the same mine show no trend of peak amplitude with explosive weight. Maximum amplitudes of the near-source data followed the same trends as the regional data suggesting that measures developed to limit in-mine ground motion might account for the lack of any increase in regional amplitudes with yield for the production blasts. Coherency estimates provide the opportunity to investigate how the waveforms compare as a function of frequency and wavelength. All elements of PDAR were used in estimating an average P wave coherence. The coherence is near 1 to high frequency (12 Hz) for two shots separated by 20 m. The coherence for two shot separated by approximately 350 m decays above 6 Hz. Finally, for the sources separated by nearly 4 km the coherence rises only slightly before decaying. These observations suggest limited applicability of coherency for identifying events from a single mine if it is large. Spectral ratios were used to investigate source scaling relations for the different yield explosions. Four similarly prepared shots with total explosive weights between 5500 and 6000 lb. were detonated to investigate source repeatability. Spectral ratio analysis identified two of the four shots as only partially detonating resulting in a reduction of long period spectral level by factors of 10 and 50. These long period reductions were accompanied by increases in source corner frequency. Production mining explosions can consist of hundreds of individual detonations. Most modeling of such blasts assume that each of the explosions performs in an identical manner. These results suggest that this assumption may need reconsideration.

Key Words: contained explosion, mining explosion, regional, calibration

OBJECTIVE

The IMS is designed to provide observational data that can be used to locate and identify events. The identification of different event types relies on the determination of characteristics that are particular to each. The signing of the CTBT has been accompanied by a cessation of nuclear testing. It has been previously shown (Denny, 1994) that contained single-fired chemical and nuclear explosions produce seismic waves that are similar. Contained, single-fired chemical explosions could therefore be used to calibrate discriminants designed for nuclear explosions. Details of moderate to small sized chemical explosions conducted in a mine are reported in order to investigate this suggestion.

Explosives are used around the world for recovering minerals and energy resources (Richards *et al.,* 1992; Heuze and Stump, 1999). Typically these explosions are delay-fired, meaning that they consist of many small explosions spread out in space and time. The monitoring system must be able to distinguish these types of explosions from a single-fired, contained explosion. The second point of relevance in this work is the quantification of observational similarities and differences between the single-fired explosions and standard mining explosions designed to move and fracture rock.

The goals of this empirical study can be broken into five elements:

1. Determination of the effect of explosive weight or yield on coupling into the regional phases Pn, Pg and Lg.
2. Empirical determination of reproducibility of regional seismograms from explosions.
3. Characterization of coherence in regional waveforms from closely spaced explosions.
4. Constraint of the source time function for single-fired, contained chemical explosions.
5. Quantification of the similarities and differences between single-fired explosions and typical delay-fired mining explosions.

A series of experiments were conducted in a mine in Wyoming on order to address these goals. Regional seismograms that are used for identifying sources are strongly affected by both the source of the waves and the regional structure through which the waves propagate. In order to eliminate propagation path effects in this study, the contained, single-fired explosions were conducted in a mine that was also conducting standard delay-fired explosions. Figure 1 illustrates the location of the cooperating mine as well as Primary IMS array, PDAR, that provided the regional seismic data for this investigation.

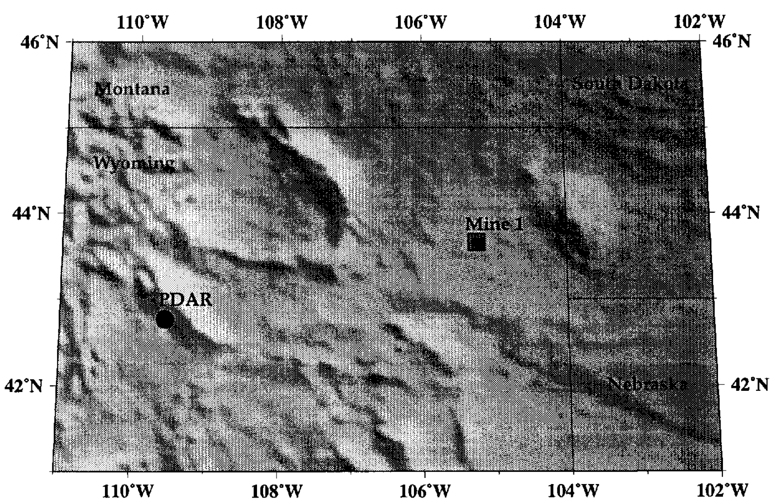

Figure 1: The experiment location. The mine is located in the Powder River Basin in NE Wyoming. The IMS Primary Array at Pinedale, Wyoming (PDAR) provides the regional data for this study.

There were seven contained, single-fired explosions with total explosive weight ranging from 5500 to 50000 lb. The number of individual boreholes in any one explosion was between 1 and 10. The spatial separations of the explosions were between 30 and 3850 m. The source characteristics are summarized in Table 1. The explosives for the contained, single-fired explosions were emplaced with a technique that was similar to that used for production shots in the mine. Boreholes were drilled to a depth of approximately 140 ft., filled with explosives and then backfilled with 40-60 ft. of stemming material. The amount of stemming was increased from that typically used in production shots (20-30 ft.) in order to assure that the event was contained. All the boreholes were drilled away from the mine free-face so that there was no relief from this surface. A single borehole configured in this manner accommodates between 4000 to 6000 lb of explosives. Multiple boreholes fired simultaneously were used for the higher charge weight shots. In these cases the boreholes were spaced approximately 32 ft apart and wired to detonate simultaneously.

Table 1: Shot Characteristics

SHOT	SIZE (lb)	Number of BOREHOLES	Distance to S1 (m)
S1	5500	1	-
S2	5500	1	30
S3	5500	1	70
S4	6000	1	90
S5	12000	3	390
S6	16000	4	420
S7	50000	10	3820

Overhead SPOT imagery of the mine illustrates the spatial distribution of the explosions relative to production activities in the mine. As illustrated in Figure 2, the mine encompasses an area that is approximately 5 km by 7 km. Shots 1 through 6 were detonated in relatively close proximity to one another. Because of its increased size, Shot 7 was detonated in the south of the mine far from the production facilities that were sensitive to close-in ground motions.

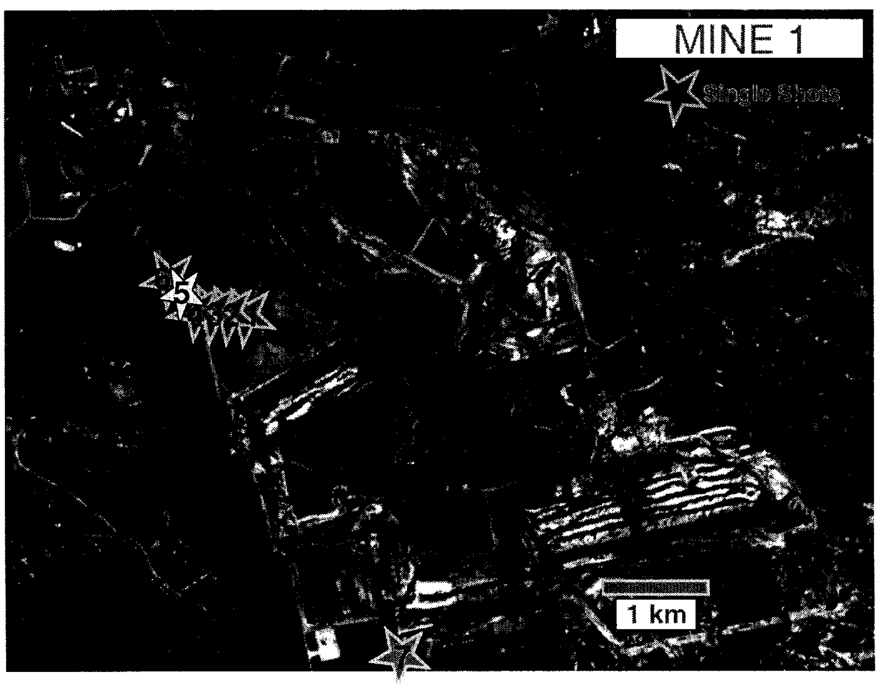

Figure 2: Overhead SPOT image of the mine along with the locations of the single-fired explosions listed in Table 1.

RESEARCH ACCOMPLISHED

1. *Determination of the effect of explosive weight or yield on coupling into the regional phases Pn, Pg and Lg.*
2. *Empirical determination of reproducibility of regional seismograms from mining explosions.*

The vertical component of motion at PDAR (PD03) from each of the seven, single-fired, contained explosions are compared in Figure 3. The relative weight of explosives in each shot is represented by the diameter of the hexagon to the right of each waveform. Each waveform is scaled to its peak in the figure with the absolute peak amplitude represented by the vertical bar to the far right. Despite the first four explosions having nearly identical explosive weight, there is over an order of magnitude variation in peak regional amplitude. Small peak amplitudes from the first two shots, S1 and S2, suggest that these two explosions did not fully detonate. Low order detonation was further substantiated by visual observations of the shot.

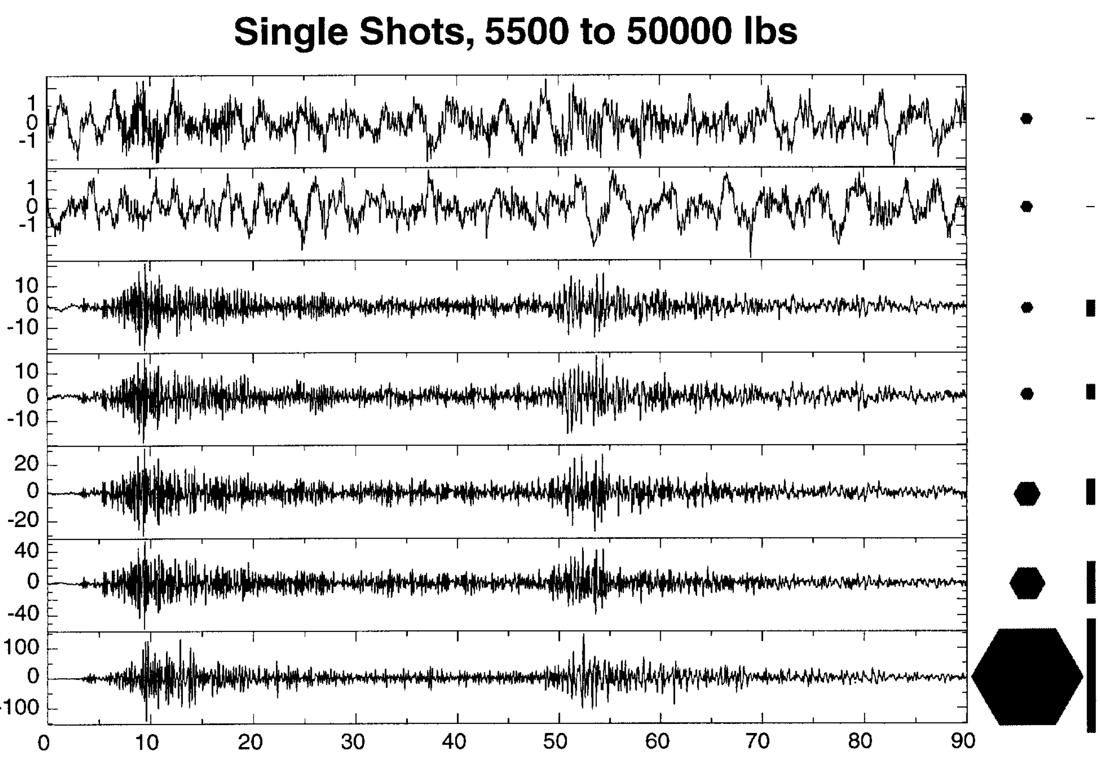

Figure 3: Relative comparison of single array element of PDAR (PD03) for the seven, single-fired explosions described in Table 1. The relative sizes of the explosions are illustrated by the size of the hexagon while the peak amplitudes of the waveforms are represented by the vertical bars to the right of each waveform.

The amount of explosives and delay pattern in a mining explosion is dependent upon both the specific mining application as well as a desire to minimize close-in ground motions to near-by buildings. These requirements limit the largest explosions in a particular application and may be responsible to some extent for a maximum expected regional magnitude from mining explosions. In order to test this hypothesis, close-in velocity measurements (7-11 km from source) were made for the single shots that could be compared to the regional measurements at PDAR. The close-in waveforms are reproduced in Figure 4. The relative comparisons of peak amplitudes for the close-in data are consistent with the regional observations. In both data sets, the first four shots, despite having the same amount of explosives, have nearly a factor of 50 variation in amplitude. The correlation between the regional and close-in amplitudes is supportive of the idea that blasting practices imposed to limit ground motion within the mine may be reflected in the regional observations.

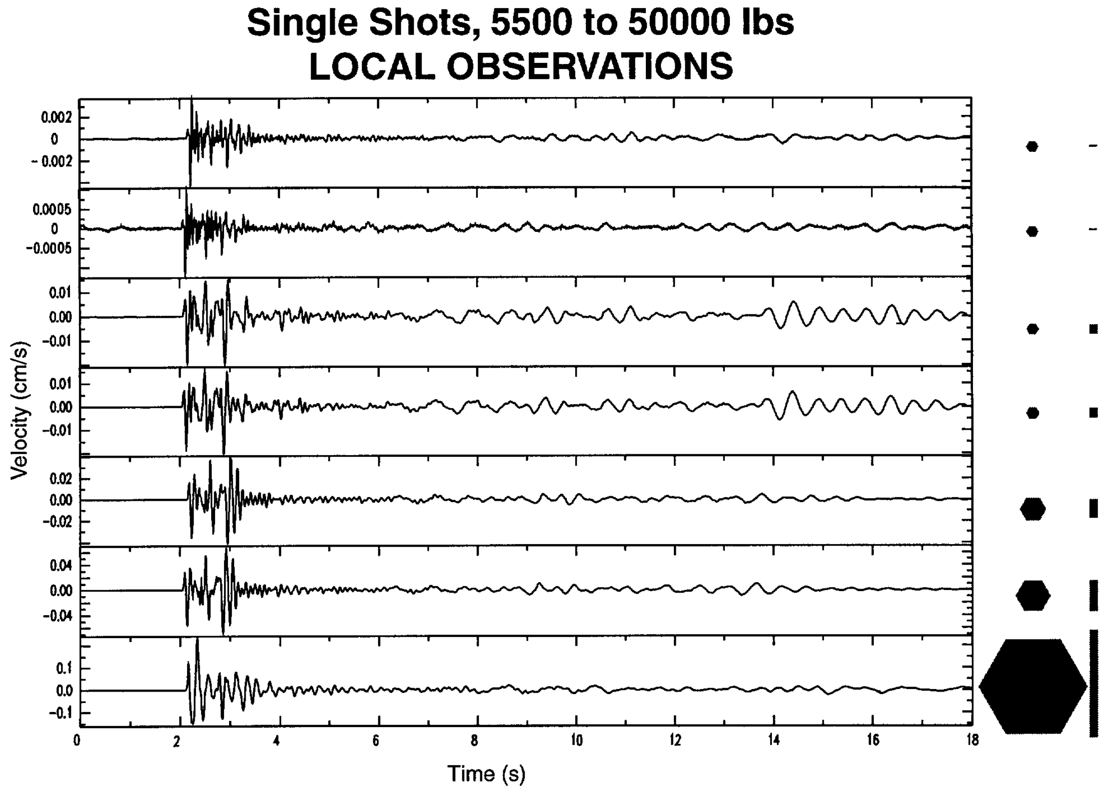

Figure 4 Relative comparison of close-in (7-11 km from source) vertical velocity records for the seven single-fired explosions described in Table 1. The relative sizes of the explosions are illustrated by the size of the hexagon while the peak amplitudes of the waveforms are represented by the vertical bars to the right of each waveform.

The first two of the four similar sized calibration explosions did not fully detonate as reflected in the peak amplitudes close-in and at regional distances. Not only is the amplitude smaller for the first two shots but the close-in data illustrates that the data is characterized by a higher source corner frequency also consistent with a low order detonation. All four of these shots were prepared in a similar manner and illustrate that one might expect significant variations in explosion performance among holes in a typical mine production shot.

Peak P_n, P_g, and L_g amplitudes were measured for each of the single-fired explosions at PDAR. Discarding the first two events, which appear to have detonated anomalously, the peak amplitudes for each of the regional phase increase with total explosive weight (Figure 5). The increase in P_g and L_g amplitudes with explosive weight is nearly identical. P_n has a much reduced amplitude at these ranges (~360 km) and increases with explosive weight at a reduced rate. These results suggest that for this path that one would have to call upon a different magnitude-yield relation for the different regional phases. The P_n amplitudes are small but are above background noise although the small size of these events may result in different components of the wave being used in the peak amplitude measurement. This effect might lead to problematic estimates for this phase.

The apparent linear relation between explosive weight and peak regional amplitudes for single-fired explosions was compared to data from delay-fired mining explosions. The mine in which the single-fired explosions were conducted routinely detonated delay-fired explosions for the purposes of removing overburden (cast blast) and for fracturing coal after removal of overburden (coal shots). The cast shots use the largest amount of explosives with

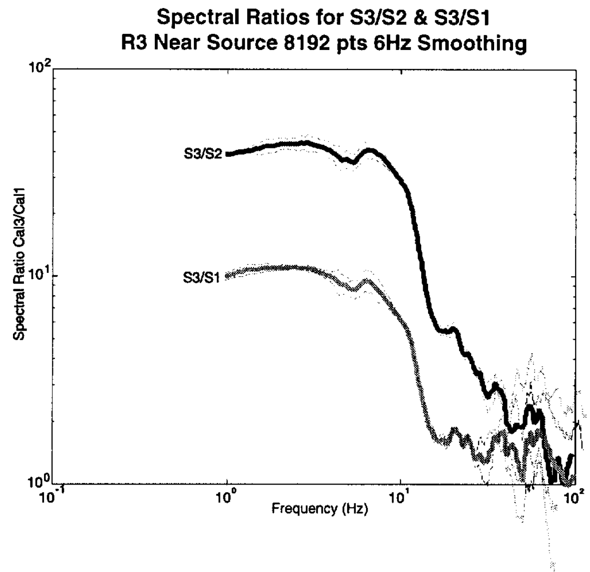

Figure 9: Average spectral ratios using close-in data for sources S1, S2 and S3

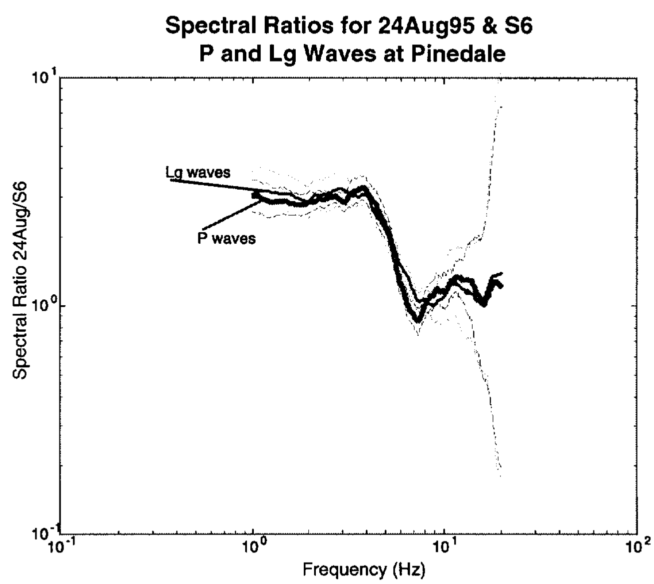

Figure 10: Spectral ratios between S7(24Aug95, 50000 lb.) and S6 (16000 lb.). Spectral ratios were estimated using PDAR and P and Lg waves.

5. *Quantification of the similarities and differences between single-fired explosions and typical delay-fired mining explosions.*

The primary difference between the single-fired explosions and the delay-fired explosions that has been illustrated is the different dependence of peak amplitude on yield. The peak amplitudes of regional Pn, Pg and Lg waveforms

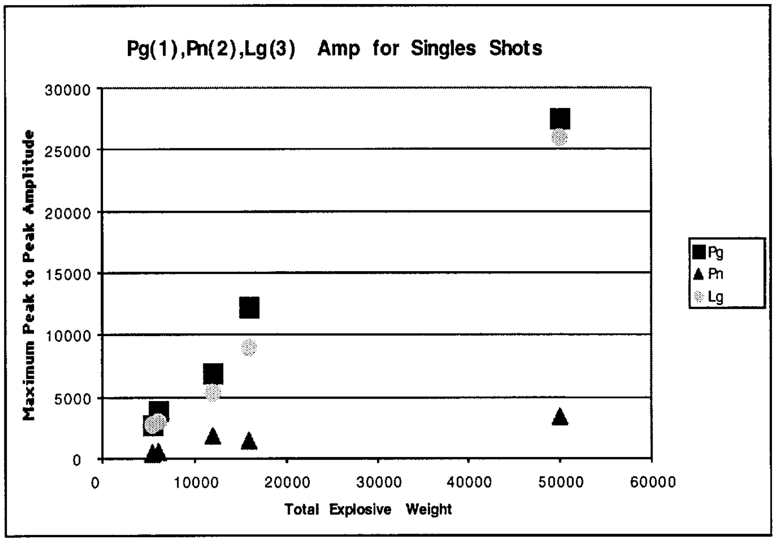

Figure 5: Peak amplitudes of the regional phases P_n, P_g, and L_g at a single array element of PDAR for each of the single-fired explosions that fully detonated as determined from close-in observations. These amplitudes are plotted against total explosive weight.

the highest powder factors. Peak amplitudes from both cast and coal shots were measured on vertical seismograms at PDAR for comparison to the single-fired shots thus allowing the effects of delay-firing on regional amplitudes to be assessed. Peak amplitude comparisons for P_g are reproduced in Figure 6.

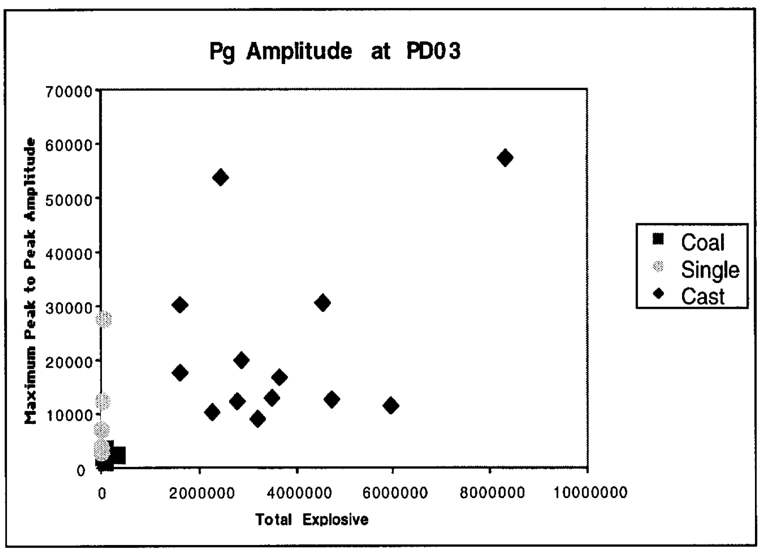

Figure 6: Peak amplitudes of P_g for the single-fired explosions (circles), large cast shots (diamonds) and the smaller coal shots (squares). The linear relation between explosive weight and peak amplitude is only observed for the single-fired explosions.

The coal shots (squares in Figure 6) with their low charge weight to coal mass (low powder factor) produce the smallest amplitudes and unlike the single-fired explosions show no increase in amplitude with explosive weight. The cast shots (diamonds in Figure 6) although quite large (several million lb.) produce peak amplitudes similar to the largest single-fired explosion (50,000 lb.). The delay-firing eliminates any relation between explosive weight and peak amplitude. These results suggest that mining explosions as observed at regional distances may produce magnitudes that are not correlated with the explosive weight of the entire explosion.

3. Characterization of coherence in regional waveforms from closely spaced explosions.

The spatial distribution of the single-fired explosions (30 m to nearly 4 km) provides the opportunity to investigate the decrease in cross-correlation or coherency in regional waveforms with increasing source separation. The map in Figure 2 illustrates the spatial distribution of the sources. We focus on coherency estimates as they provide an opportunity to investigate how the waveforms compare as a function of frequency and wavelength. Estimates of coherency are dependent upon the product of the bandwidth of smoothing (B) and the time window (T) used for estimating the spectrum (Harris, 1991). All the elements of PDAR were used to make a mean coherency estimate and a standard error determination for each comparison. Figure 7 compares the coherency for S4 & S3 with a source separation of 30 m, S6 & S3 with a source separation of 350 m and S7 & S3 with a source separation of nearly 4 km.

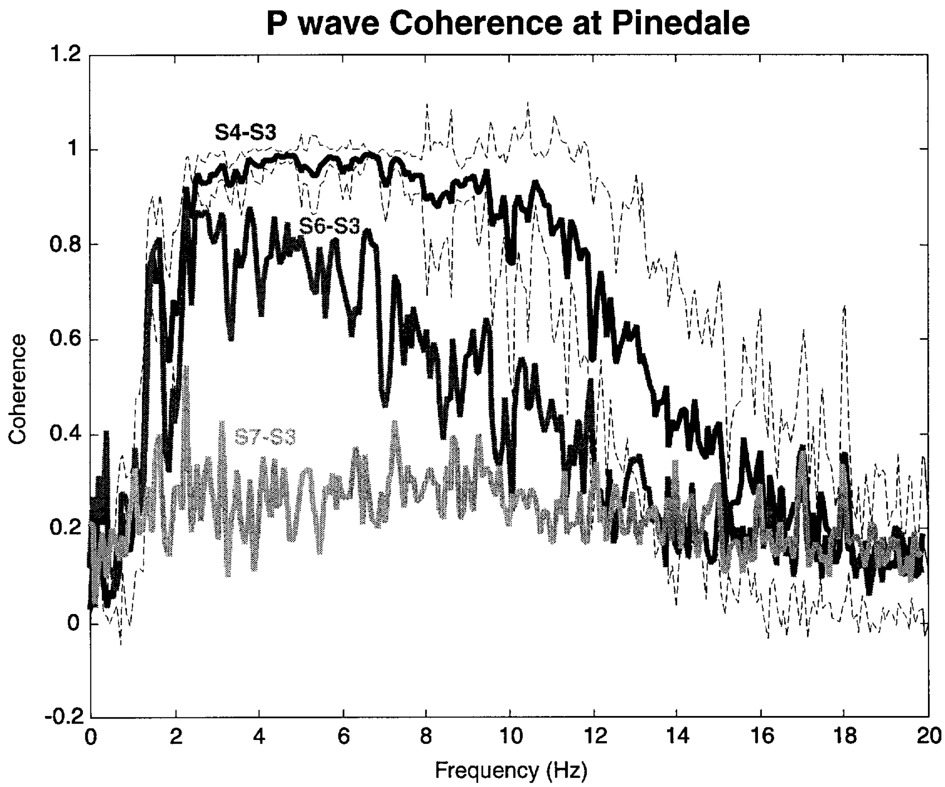

Figure 7: Coherence estimates for P waves at PDAR. Dotted lines represent plus or minus one standard deviation. Sources S4 & S3 are separated by 30 m, S6 &S3 by 350 m and S7 & S3 by 4 km.

Coherence is nearly 1 to high frequency (12 Hz) for the two closely spaced shots. The intermediate spaced shots (350 m) produce a coherence that is large to 6 Hz and then decays. The coherence for the two shots separated by nearly 4 km is small across the entire bandwidth. With P velocities ranging between 6 and 8 km/s, the results suggest that coherence decay at sub wavelength source separations. The spatial dimension at which this decay becomes significant is equal to or less than the spatial dimension of the mine where these experiments were conducted.

4. *Constraint of the source time function for single-fired, contained chemical explosions.*

Simple spectral ratios utilizing the spectra from the individual single-fired explosions provides a mechanism for quantifying variations in spectral shape that can be attributed to the source function (Stump *et al.,* 1999). The modulus of the spectral estimate from each explosion is compared, eliminating the phase and its variation identified in the coherency estimates. The first example is for two sources (S4 & S3) of identical yield. Spectral ratios were estimated for each array element at PDAR and a mean formed (Figure 8). Additionally spectral ratios were estimated using a single, three-component station in the near-source region. This provides the opportunity to compare near-source and regional source estimates and extend the source comparison to higher frequency.

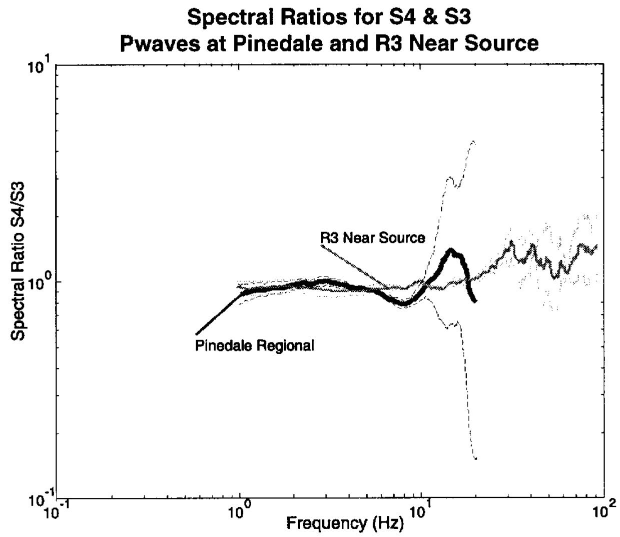

Figure 8: Spectral ratios between two identical single-fired shots (S4 &S3). The thick line is the spectral ratio estimated using the array elements at PDAR. The thin line is the spectral ratio using a single, three-component station from within the mine.

The spectral ratios at local and regional distances in Figure 8 are consistent. They both indicate that the spectra from the two shots are nearly identical (ratio of 1). The rise in spectral ratio above 10 Hz for the regional data is accompanied by an increase in standard deviation. The higher bandwidth close-in data indicates that the ratio remains flat to higher frequencies.

The close-in data can be used to investigate the characteristics of the two single-fired shots that produced the small amplitudes (S1 & S2) illustrated earlier in Figure 3 and 4. Spectral ratios for these shots compared to S3 are given in Figure 9. These spectral ratios suggest that S1 was reduced by a factor of 10 (~500 lb.) and S2 was reduced by a factor of 50 (~100 lb.). It is interesting to note that only two of four identically prepared boreholes produced maximum seismic energy. A single mining explosion consists of hundreds of such boreholes and typical modeling assumes each borehole performs in an identical manner.

In each of the previous examples, the sources used in the comparison were of similar size. In Figure 10, S6 (16000 lb.) is compared to S7 (50000 lb.). The spectral ratios for both P and Lg provide similar estimates of the source differences. The ratios are flat at long periods with the relative size indicative of the factor of three difference in absolute source size. The corner frequency of the larger explosion is below 4 Hz where the ratio begins to decay and then reached a plateau at the second corner of 7 Hz.

from the single-fired explosions were found to reflect the total weight of explosives whereas peak amplitudes for delay-fired explosions did not.

Additional work has been undertaken to investigate other differences in the waveforms from single-fired and delay-fired explosions that might be useful for identification purposes (Hedlin *et al.*, 1999). Both the single-fired explosions and the delay-fired explosions are rich in high frequency P energy. At intermediate frequencies, Lg energy dominates from both source types. It is only at the longest periods (4-10 s) that there is significant differences between the single-fired and cast shots with the cast shots generating intermediate frequency surface waves and the single-fired shots producing none.

CONCLUSIONS AND RECOMMENDATIONS:

The conclusions that can be drawn from this empirical study are four.

1. Over an order of magnitude variation in explosive performance is observed from four identically prepared boreholes. This variation may effect the modeling of delay-fired mining explosions which often assumes linear superposition and similar coupling among sources.
2. Scaling of peak motions observed near-source and at regional distances for single-fired explosions are consistent. Since mines are constrained to control ground motions within the mine, this result suggests that peak motions at regional distances may be similarly controlled.
3. Significant decreases in correlation of P waves for closely spaced sources observed at regional distances were observed. The decrease is sub wavelength and suggests that significant differences can be expected for shots distributed across large mines.
4. Single-fired explosions produce an apparent linear increase in peak amplitude with explosive weight. Delay -fired explosions produce no such trend. Relatively modest sized contained single-fired explosions (50,000 lb.) produce regional signals comparable or greater to production mining explosions including millions of pounds.

The results of this study provide a basis for design and implementation of calibration explosions under a CTBT using typical emplacement and detonation equipment available at a mine.

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